LA-UR -91-2119

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under [illegible]

LA-UR--91-2119

DE91 016086

TITLE: OPTICALLY PUMPED POLARIZED ION SOURCES

AUTHOR(S): Olin van Dyck

SUBMITTED TO: The proceedings of the
Fourth Intersections Conference
May 26-28, 1991
Tucson, Arizona

DISCLAIMER

LOS ALAMOS

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Form No. 836 R4
ST No 2629 5/91

OPTICALLY PUMPED POLARIZED ION SOURCES

Olin B. van Dyck
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

Recent operating experience and development of the Optically Pumped Polarized Ion Source (OPPIS) projects at LAMPF and other Laboratories is reviewed.

1. INTRODUCTION

Recently there have been several thorough and scholarly reviews[1,2,3,4,5] on OPPIS technology. This brief article will give an update of recent operating experience and development and some speculation on possible future performance.

Because 1 W of laser light corresponds roughly to 1 particle-ampere of photons, presently available multi-watt lasers could provide a nearly infinite source of angular momentum for spin orientation of ions. However, with available laser wavelengths, a polarizable electron donor medium (alkali vapor) must be used to transfer spin angular momentum from the laser beam to the particle beam. In present sources, the beam extracts very little of the spin in the vapor; most of the polarization escapes from the usable volume of the vapor on the thermal drift of the alkali atoms.

The use of an exchange medium also means that two charge exchanges are necessary to produce polarized H^- from incident H^+. Although the maximum double-charge-exchange efficiency estimated from the cross sections is 6-7%, finite apertures and the long neutral-beam drift (50-60 cm or more) in all realized OPPIS configurations apparently set the net efficiency to less than one-tenth of the maximum. So with the maximum available initial H^+ flux on the order of 100 mA, H^- currents of order 100 μA have been achieved in low-duty-factor sources, and 20-40 μA at high duty factor.

These considerations have led to the more or less standard source configuration and performance described in Section 2. Section 3 reviews some recent work directed towards source optimization. Section 4 describes alternative source configurations at the Moscow Meson Factory (MMF), and Section 5 tabulates performance.

2. THE STANDARD OPPIS CONFIGURATION

Fig. 1 is a block diagram of the LAMPF OPPIS configuration (the systems at KEK [Tsukuba, Japan] and TRIUMF [Vancouver, Canada] are roughly similar). The 1.6-T axial magnetic field for the polarizer cell is provided by a superconducting magnet with a 14-cm bore, which allows enough space radially for adequate vacuum pumping of the hydrogen gas flowing out of the ECR source; this is important for minimizing the (unpolarized) H^0 beam formed in this region. An additional set of superconducting coils in the magnet provides a plasma confinement zone between the two ECR resonances at 0.7 T. Table I (in the Conclusion) gives a few of the details for the sources at the four Laboratories.

It is important to optimize the ECR ion optics to maximize the final H^- current rather than the maximum ECR proton current. An important development at LAMPF was the discovery of the "accel-accel" biasing mode, which has the middle electrode at the same polarity as the first (4 kV) electrode. TRIUMF also found that accel-accel biasing is better and KEK is in the process of evaluating this scheme.

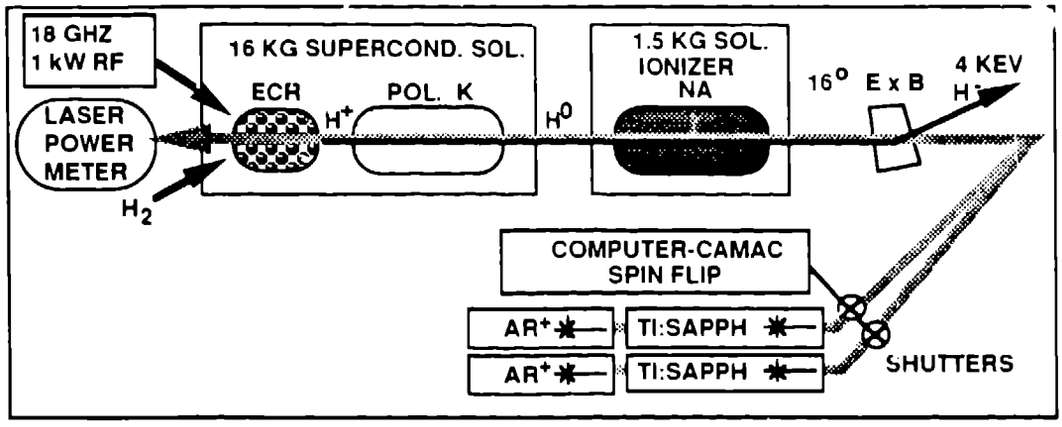

Fig. 1. OPPIS configuration at LAMPF, similar to KEK and TRIUMF.

With accel-accel biasing, the extraction potential is only about 1 kV and the extracted proton current is considerably lower than with "accel-decel," but the final beam flux is seven times higher.[6] The gain is probably due to reshaping of the plasma sheath to make the particle trajectories more parallel, but may also be related to space charge neutralization. Empirical optimization has led to the electrode configuration sketched in Fig 2. Effectiveness of the accel-accel mode appears to be limited to particular electrode geometries. More details are given in refs.[5,6].

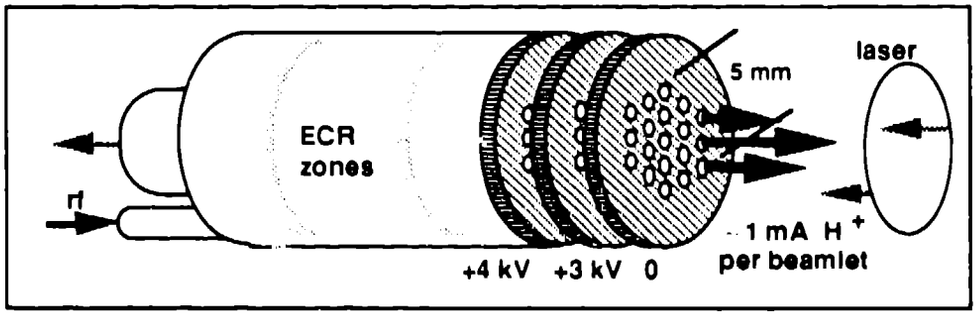

Fig. 2. ECR configuration. In the LAMPF version, the first (4 kV) electrode is 1.5 mm thick and has 19 or 37 1.0-mm holes. Electrode spacing is 1.0 mm.

3. OPTIMIZING POLARIZATION AND BEAM CURRENT

The H^- ion current from OPPIS reaches a limit set by neutralization equilibrium as the polarizer cell thickness is increased; for the alkalis Na-Cs, equilibrium thickness is around 2-5 x 10^{14} at/cm^2. Fig. 3 shows measurements[7] at LAMPF indicating that with an ECR proton beam diameter of 5 mm, the part of the vapor sampled by the ion beam can be adequately polarized by available laser power (8W) up to at least a K thickness (8×10^{13} at/cm^2) which gives about 75% of the maximum current.

The data in Fig. 3 can be fit to a simple model[7,8] which incorporates the logarithmic approach of polarization to its asymptotic value with increasing laser power; the asymptotic value thus found is about 70%. This value, and the experience at all the Laboratories, suggests that the maximum practical polarization is in the range 65-70%.

The final ion-beam polarization is set by the product of the vapor polarization P_K times the three transfer efficiencies:

$$P^- = P_K \times (\text{charge-exch spin eff'y}) \times (\text{Sona eff'y}) \times (\text{ionizer spin eff'y}) \times (\text{background beam dilution factor})$$

Although each factor is believed to be above 90%, it is difficult to know the factors sufficiently accurately to make a confident prediction of final polarization, or even to be sure which term to attack in source optimization. The first three "efficiencies" in the equation are coupled functions of the magnetic fields in the source and do not lend themselves to independent determination. In particular, the Sona hyperfine spin-exchange efficiency is a function of the field shape at the exit of the polarizer and the entrance of the ionizer; changing either field also changes the Sona efficiency.

There is some completely unpolarized contribution to the neutral beam flux from the H^0 formed from hydrogen gas near the ECR source and alkali vapor outside of the uniform magnet field region where the laser beam is absorbed. The former, estimated by measuring beam current vs alkali density at low temperature, appears to be a few percent effect. The latter is estimated from the cell geometry to be very small.

The alkali vapor polarization in the central magnetic field region is calculated from the ratio of measured Faraday rotation angles in the vapor when polarized and unpolarized. The "unpolarized" angle is small and contributes typically 5-10% to the error on the vapor polarization. Thus it is difficult to know the absolute value of the vapor polarization with sufficient accuracy to tell the difference between 90 and 95%. A further ambiguity arises because the probe laser beam does not sample exactly the same vapor volume as the particle beam.

Clearly it becomes an inefficient use of laser power to run the polarizer cell too

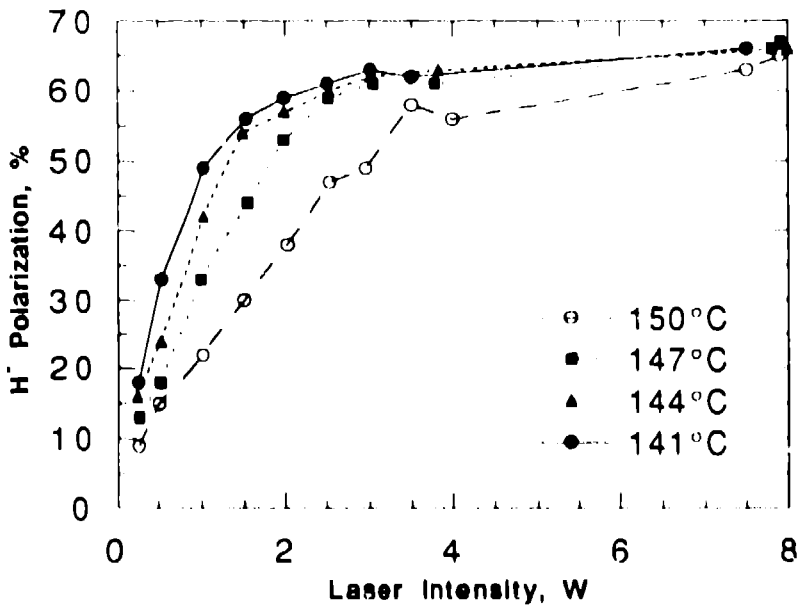

Fig. 3. Beam polarization (measured at 800 MeV) vs laser power at various K temperatures (K density from 4 to 8×10^{13} at/cm^2).

near equilibrium thickness. There are at least two other factors which limit usable vapor density.

The first factor is radiation trapping,[9] which is the reabsorption by the vapor of the vapor fluorescence radiation. Since this competes with optical pumping by the polarized laser beam, it has a depolarizing effect. For K, the radiation trapping limit on polarized vapor density sets in near charge-exchange equilibrium thickness with a 10-cm cell; for Na, the radiation trapping limit is almost a factor of two lower[10]. The second factor is laser-induced vapor thinness. This phenomenon, seen at LAMPF, KEK, and MMF, causes a reduction in final beam current at high density and laser power. It is not completely understood, but may be an ionization-recombination effect occurring with a high density of excited alkali atoms.[2]

Since the optical pumping cycle takes on the average three photons to flip the electron spin in an atom, one expects that the number of polarized atoms in the vapor is proportional to the laser power absorbed by the vapor, at least in constant geometry. The beam polarization and laser absorption data from ref. 7 has been transformed to give the number of polarized atoms in the vapor per unit of absorbed power and is shown in Fig. 4.

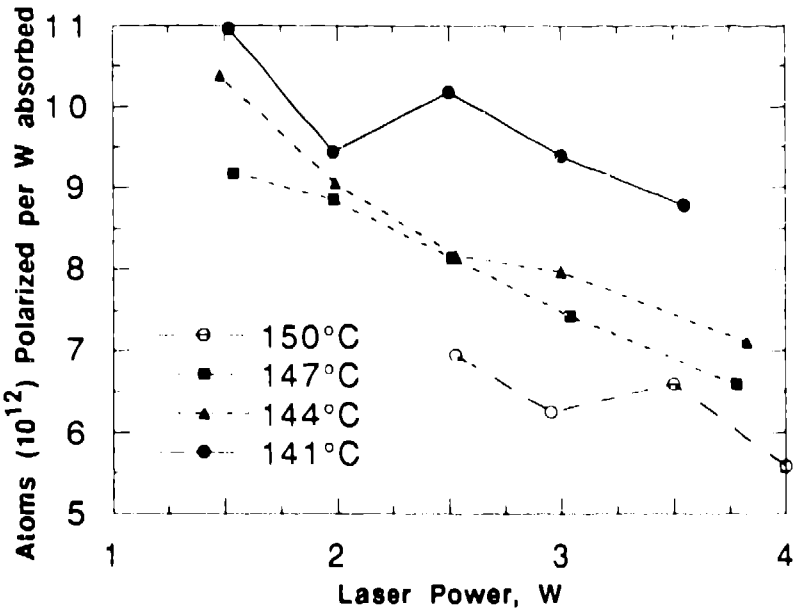

Fig. 4. Atoms polarized per watt of absorbed laser power.

Although the absorption measurements have considerable fluctuations because of the interference of the ECR hole pattern with structure in the laser-beam intensity profile, the trend of decreasing photon efficiency at higher powers and densities is clear; in fact, over the range graphed, the efficiency varies by a factor of two. We do not understand this large effect, but suggested causes are radiation trapping and stimulated emission. Both effects would be accentuated by nonuniform spatial distributions of vapor density and laser intensity.

Evidently there are several limits or constraints on increasing source current by increasing vapor thickness. Other coordinates of the problem are injected beam current density and diameter, and neutral beam acceptance. To increase current density, KEK is able to use multiaperture electrodes with very thin metal webs, under 0.25 mm,

between holes to achieve 80% transparency. Although at higher duty factor (LAMPF and TRIUMF) the web must be a little thicker, typical transparency (open area inside the hexagon) is still 70%.

Empirical methods may still give further modest gains in neutral beam acceptance by improving the ECR ion optics. It is not clear whether this problem is computationally tractable because of space-charge effects, the presence of many metal surfaces, complicated geometry, and high magnetic field.

Increasing the radial dimensions of the system will increase source current up to the limits set by other apertures (ultimately, the accelerator acceptance). With the standard ECR configuration, the proton current is increased simply by adding another set of holes to the outside of the hexagonal pattern. However, additional laser power is needed to obtain the same polarization in the larger volume. It is interesting to note that the laser power only needs to increase as the first power of radius, since the outward flux of polarized atoms is proportional to radius, whereas the number of atoms inside is proportional to radius squared.

In the LAMPF source, changing from 19 to 37 holes (7 mm across the hexagonal flats) nearly doubles the beam current. However, research program requirements in 1990 were better served by the 7% higher polarization with the lower-current beam. Preparation for LAMPF 1991 operation has been to ensure availability of 20-μA peak current and 65% polarization. The increased polarization is obtained by doubling the laser power over the single-laser pumping configuration shown in Fig. 1. This is achieved by shifting the laser frequencies during spin flip[7] so that both Ti:Saf lasers can be used to pump both spin states.

Recent operation at TRIUMF used 61 1-mm holes in a hex pattern 10.4 mm across the flats. In subsequent beam development,[5,11] it was found that a 31-hole pattern (derived from a 37 hole hex pattern with the corners omitted) raised the beam polarization above 60% with less than a factor of two loss in accelerated beam current; this is the planned mode of operation later this year.

In addition to converting to Ti:Saf lasers this year, TRIUMF will attempt to use Rb in the polarizer cell to raise the radiation trapping limit on vapor density. Preliminary results from MMF also indicate that Rb is superior.

4. ALTERNATIVE CONFIGURATIONS

The highest peak current in OPPIS has been achieved with multiple-charge-exchange proton-beam injection[2], a method which appears to be limited to very low duty factor, as indicated in Table I. This high current shows however that optimum injection of the proton beam is essential for maximum performance.

This method also leads naturally to the scheme of spin exchange. If a neutral atomic hydrogen beam instead of a proton beam is injected into the polarized vapor, and if the vapor is thick enough to ensure several electron (spin) exchanges, the emergent neutral beam can be highly polarized. In the MMF system, neutral beam injection is accomplished simply by eliminating the stripper cell in front of the polarizer. However, achieving a highly polarized and sufficiently thick vapor, about 10 times thicker than necessary in the charge-exchange configuration, requires high laser power and circumventing the other difficulties mentioned above at high density. Present development at MMF is to evaluate a K:Rb mixture pumped with pulsed Ti:Saf or Alexandrite lasers having up to 1 kW peak power.

5. CONCLUSIONS

Table I shows the performance achieved in beam delivery for research and in development at the four Laboratories with optically polarized sources. Although the low-duty-factor sources have a clear advantage in peak performance, the 100%-duty facility has the edge in average current, 5 μA, accelerated and delivered for research, with the 10%-duty facility not far behind with up to 1 μA average current available. (The large loss of current from the injector to accelerator output at TRIUMF arises from the cyclotron acceptance.) With careful optimization of the standard configuration, it is not unreasonable to expect perhaps within two years an ion source capable of high-duty-factor operation at 65% polarization and 100 μA with normalized emittance (90% of area) under 1 π mm-mrad. On the other hand, development of alternative source configurations--maybe not in the same time frame--may jump over these limits. Success of the OPPIS method provides a good example of the benefits of interlaboratory cooperation; this continues today.

Table I. OPPIS parameters for production and development at the four Laboratories.

	H+ source	Alkali	Field T	Laser	Eff.pwr W	I- peak μA	P- %	df %
KEK prod	ECR	Na	1.2	FLD*	>35	120	65	0.2
MMF dev	DuoPl.	Na	1.2	FLD*	17J	400	65	0.01
LAMPF prod dev	ECR	K	1.6	Ti:Saf	3.5 8	17 (1**) 22	62 65	10
TRIUMF prod dev	ECR	Na Rb	2.2	Dye Ti:Saf	6	25 (5**)	61	100

* FLD = flash-lamp-pumped dye laser **average accelerated current

REFERENCES

1. R. L. York, "Recent Developments in Optically Pumped Polarized Ion Sources," Proceedings of the International Workshop on Polarized Ion Sources and Polarized Gas Jets, ed. Y. Mori (Tsukuba, Japan, 1990), p. 142
2. A. Zelenskii *et al*, "Status of the Optically Pumped Polarized Ion Source at INR in Moscow," *ibid*, p. 154
3. A. Ueno *et al*, "Polarization Measurement of an Atomic Hydrogen Beam Spin-Exchanged with Optically Oriented Sodium Atoms," *ibid*, p. 321
4. L. Buchmann *et al*, "Aspects of the Continuous Wave, Optically Pumped H^- Ion Source at TRIUMF," *ibid*, p. 161
5. L. Buchmann *et al*, "A DC Optically Pumped Polarized H^- Source," submitted to Nucl. Instr. & Meth. (1991)
6. R. L. York *et al*, "Operation of the Optically Pumped Polarized H^- Ion Source at LAMPF," to be published in the Proceedings of the 1991 IEEE Particle Accelerator Conference (San Francisco, 1991)
7. D. Swenson *et al*, "Optical Pumping of the LAMPF Polarized H^- Ion Source, " *ibid*
8. O. van Dyck, in Proceedings of the International Seminar on Intermediate Energy Physics (INR, Moscow, USSR, 1990) p. 65
9. D. Tupa *et al*, Phys. Rev. A33 (1986) p. 1045.
10. Y. Mori *et al*, Nucl. Instr. & Meth. A268 (1988) p. 270
11. P. Schmor *et al*, "Operational Experience with the TRIUMF Optically Pumped Polarized H- Ion Source," in ref. 6.